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Ballistic Experiments With Titanium and Aluminum Targets

April 2001

Final Report

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16. Abstract

This report describes experiments in penetration mechanics on 6Al-4V titanium and 2024-T3 aluminum. This work was accomplished by the Lawrence Livermore National Laboratory (LLNL) at the LLNL Terminal Ballistics Laboratory of the Physics Directorate under an Interagency Agreement between the Federal Aviation Administration (FAA) William J. Hughes Technical Center and the Department of Energy (DOE). The work was accomplished under the FAA's Aircraft Catastrophic Failure Prevention Program as part of its research into the turbine engine uncontainment event. The object of the experiments was to determine the ballistic speed limit of 6Al-4V alloy titanium and 2024-T3 alloy aluminum and the failure modes of the projectiles and targets. Data was obtained for both materials using various thickness plates of the test materials to simulate aircraft skins and various size and shape 6Al-4V alloy titanium projectiles. The results of this experimental work will be used to help define the type of material failures in material models of the DYNA3D finite element code, which are being developed/validated for evaluating aircraft/engine designs relative to the federal airworthiness standards and for improving mitigation/containment technology.

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EXECUTIVE SUMMARY

This report describes experiments in penetration mechanics on 6Al-4V titanium and 2024-T3 aluminum. The object of the experiments was to determine the ballistic speed limit of 6Al-4V alloy titanium and 2024-T3 alloy aluminum and the failure modes of the projectiles and targets. Data was obtained for both materials using various thickness plates of the test materials to simulate aircraft skins and various size and shape 6Al-4V alloy titanium projectiles. The results of the experimental work will be used to help define the type of material failures in material models of the DYNA3D finite element code, which are being developed and validated for evaluating aircraft and engine designs relative to the federal airworthiness standards and for improving mitigation and containment technology.

1. INTRODUCTION.

1.1 OBJECTIVE OF EXPERIMENTS.

Experiments were run to provide ballistic threshold data for materials used by the aircraft industry using controlled geometries, controlled impact conditions, and characterized materials with well-defined material properties. It was also necessary to be able to examine the targets after impact to assess the failure characteristics. There was no existing data where all these criteria were met. The ballistic data from the experiments is essential in determining failure parameters in the material models.

Two sets of fundamental experiments in penetration mechanics were conducted in the Lawrence Livermore National Laboratory (LLNL) Terminal Ballistics Laboratory of the Physics Directorate. The first set of full-scale experiments was conducted with a 14.5-mm air propelled launcher. The objective of the experiments was to determine the ballistic limit speed of 6Al-4V alloy titanium, low fineness ratio projectiles centrally impacting 2024-T3 alloy aluminum flat plates, and the failure modes of the projectiles and the targets. The second set of one-third-scale experiments was conducted with a 14.5-mm powder launcher. The objective of the experiments was to determine the ballistic limit speed of 6Al-4V alloy titanium, high-fineness ratio projectiles centrally impacting 6Al-4V alloy titanium flat plates and the failure modes of the projectiles and the target.

Radiography was employed to observe a projectile just before and after interaction with the target plate. Early in the experiment, a nondamaging, "soft-catch" technique was used to capture projectiles after they perforated the targets. Once it was realized that a projectile was not damaged during interaction with the target, a 4-inch-thick 6061-T6 alloy aluminum witness block with a 6.0- by 6.0-inch cross section was used to measure projectile residual penetration thereafter. The following data was recorded and tabulated below: projectile impact speed, projectile residual (postimpact) speed, projectile failure mode, target failure mode, and pertinent comments for the experiments. The ballistic techniques employed for the experiments were similar to those employed in an earlier study [1].

2. EXPERIMENTAL TECHNIQUES AND SPECIMEN CONFIGURATION.

2.1 TITANIUM PROJECTILES AND ALUMINUM PLATE TARGETS.

2.1.1 Launch and Measurement Techniques.

In order to launch projectiles of very low mass at repeatable speeds (under the same launch conditions) from the LLNL standard 14.5-mm single-stage powder gun, the breech mechanism was modified. Because the projectile speed range of interest was 200 fps to 1000 fps, neither conventional cartridge cases filled with powder nor ullage fillers within the cases to reduce the volume of powder would provide both sufficiently low speed and repeatability. The conventional 14.5-mm powder breech was replaced with a low-pressure (and low-cost) solenoid activated reservoir gas breech, as shown in figures 1 and 2, respectively. A 300 psi fast-acting solenoid was installed. This change resulted in reliable projectile speeds between 195 fps and 735 fps for projectiles ranging in mass from 2.0 to 9.5 grams. However, even a fast-acting

solenoid is relatively slow. The slow reaction time of the solenoid places an upper bound on projectile speed because the pressure buildup within the gun is limited. The air breech was not needed for higher projectile speeds. For higher projectile speeds in this projectile mass range, the ullage filler technique employing conventional small arms propellants is usually employed by LLNL.

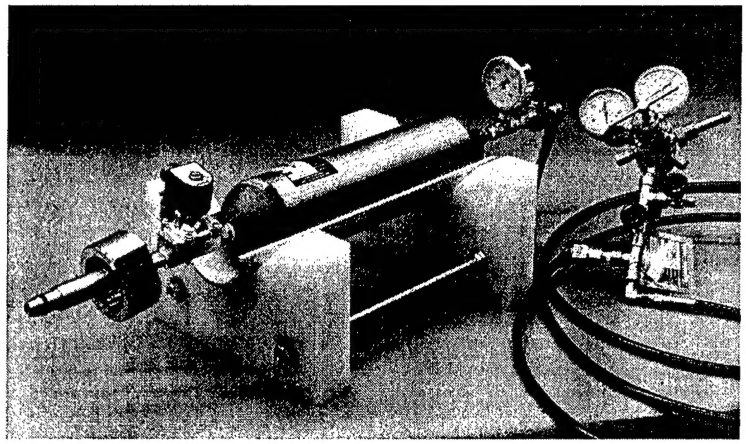

FIGURE 1. SOLENOID ACTIVATED GAS BREECH

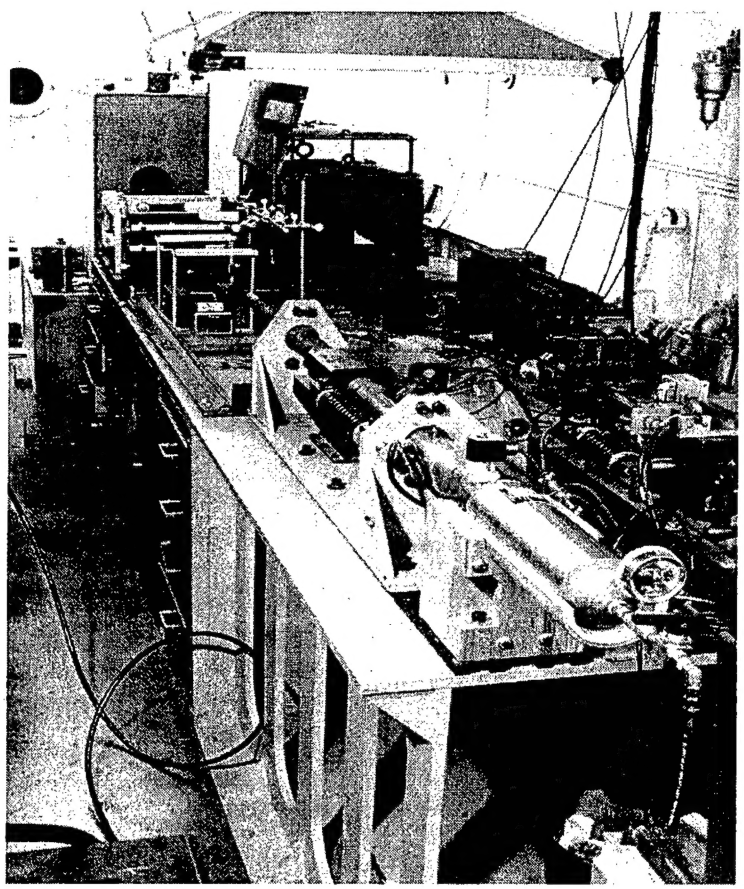

FIGURE 2. GAS BREECH, LAUNCHER, CHRONOGRAPH, AND PROJECTILE TRAP

Each projectile was seated in a sabot (projectile carrier) before being placed in the launcher. The sabot held the projectile and was the interface between the projectile and the internal surfaces of the launcher. Each sabot was machined from polypropylene in the geometry of a hollow, thin-walled right-circular cylinder with a concave base.

The first experiments used a conventional flash radiography system to determine projectile speed, orientation just before impact, and projectile residual speed and orientation after target perforation. Radiography was used to estimate residual projectile speed and orientation after target perforation. A compact counter chronograph was employed to determine preimpact projectile speed as shown in figure 3. Foil switch triggers were used initially. However, there was concern that the projectiles were being disrupted before they reached their targets because the projectiles have such small mass. The chronograph system proved to be very reliable and allowed faster production of experiments since it eliminated fabrication of foil switches and processing of additional radiographic film. Once the proper projectile attitude after launch was demonstrated, the changeover to the chronograph system was easy and reliable.

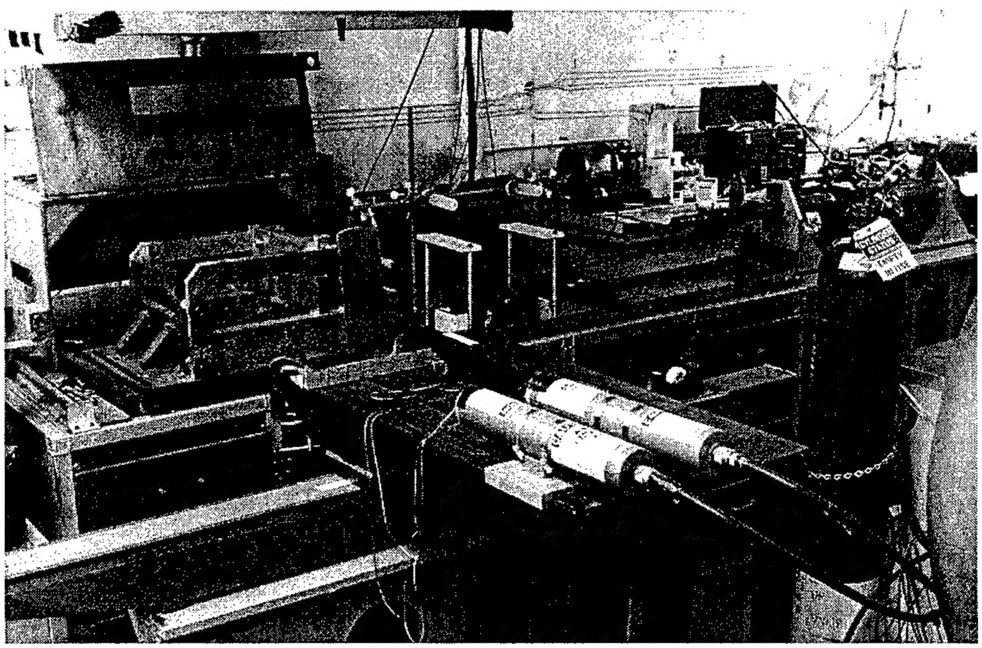

FIGURE 3. CHRONOGRAPHIC AND RADIOGRAPHIC HARDWARE

2.1.2 Specimen Configuration (Titanium Projectiles and Aluminum Targets).

The first set of full-scale experiments was conducted with a 14.5-mm air propelled launcher. The object of the experiments was to determine the ballistic limit speed of 6Al-4V alloy titanium, low-fineness ratio projectiles, centrally impacting 2024-T3 alloy aluminum flat plates and the failure modes of the projectiles and the targets.

Three different projectile geometries were employed for the experiments. The projectiles were machined from 0.50-inch-diameter titanium bar stock. The materials specification was MIL-T-9047G, Condition A, AM 2 (6Al-4V titanium). The hardness of the titanium was

Rockwell C (RC 37). Chemical analysis of the titanium stock yielded the following percentages of trace and alloying elements (the balance being titanium):

N: 0.008	Fe: 0.1950
C: 0.0165	O2: 0.1600
H: 0.0029	Al: 6.2500
Y: 0.0010	V: 4.1300

Mechanical properties of the titanium bar stock were reported in reference 2:

Tensile Strength (ksi) (longitudinal):	161.2
Yield Strength (ksi) (0.2% offset):	142.1
Percent Elongation:	15.0
Percent Reduction in Area:	54.8

Three projectiles were employed for the experiments: (1) a fragment simulant projectile (FSP), (2) a right circular cylinder projectile with fineness ratio of 1.0 right circular cylinder projectile (RCC1), and (3) a right circular cylinder projectile with fineness ratio of 0.2 (RCC0.2). The projectile diameter was held constant at 0.50 inch for all projectiles. Figure 4 displays the geometry of the FSP. FSPs are standardized projectiles used by the military to characterize the impact of "chunky" projectiles against a variety of targets. The RCC1 projectiles were used to determine the sensitivity of ballistic performance to a modest change in nose shape. The lengths of the FSP and RCC1 projectiles were the same. The RCC0.2 projectiles were chosen to record the effect of a fundamentally one-dimensional, nonsteady interaction between projectile and target.

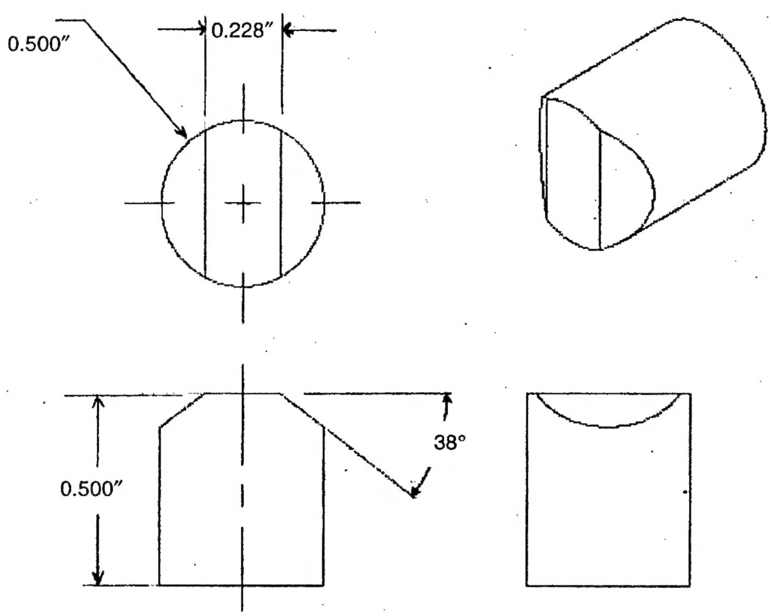

FIGURE 4. FULL-SCALE PROJECTILE GEOMETRY

The target plates were composed of 2024-T3 alloy aluminum manufactured by Kaiser Aluminum. The 2024-T3 alloy aluminum was manufactured to AMS 4037 (revision M) and ASTM-B-209 (revision 96). Commercial aircraft skin is usually composed of an aluminum alloy in thicknesses between 0.05 and 0.010 inch. The target plates all had a 6.0-inch by 6.0-inch cross section. Target plates of thicknesses 0.05, 0.10, and 0.15 inch were ballistically evaluated. Chemical analysis of the aluminum plates yielded the following percentages of trace and alloying elements (the balance being aluminum):

Si: 0.08	Fe: 0.22
Cr: 0.016	Cu: 4.76
Zn: 0.07	Mn: 0.65
Ti: 0.03	Mg: 1.38
V: 0.02	

Mechanical properties of the aluminum plate were reported in references 3 and 4:

Tensile Strength (ksi) (longitudinal):	46.0
Ultimate Tensile Strength (ksi):	67.3
Percent Elongation:	18.0

2.2 TITANIUM PROJECTILES AND TITANIUM PLATE TARGETS.

2.2.1 Launch and Measurement Techniques.

The experiments required the launch of high fineness ratio large projectiles. These were the largest projectiles ever launched from the 14.5-mm single-stage powder launcher. However, even though the projectiles were massive, the case volume was too large to produce reliable, repeatable projectile speeds under 1,000 fps.

An ullage filler, which is the standard LLNL method, was then employed. An ullage filler is a solid cartridge case that is machined down the centerline to the gun bore diameter with a smaller diameter powder chamber at its base. This produces a much smaller ratio of powder-to-chamber volume and consequently better utilizes the burning characteristics of powder. Employing the ullage filler approach and the appropriate powder produced repeatable projectile speeds of 300 fps to 1500 fps.

The launch of very long projectiles proved to be damaging to the counter chronograph because the projectiles tended to rebound off the target face on nonperforating impacts. In addition, a projectile with a fineness ratio of 20 had a length that exceeded the distance between the light sensors of the chronograph, thereby producing unreliable (false) speed readings. Therefore, to measure projectile speed reliably, a pair of foil switches spaced at a known distance apart and connected to an interval counter were used. Unlike the previous testing described in paragraph 2.1.1, the foil switches were acceptable for this test because the size of the projectiles was much greater, and the foil switches did not disrupt the projectiles as with the smaller ones. Each foil switch consists of two 0.002-inch-thick copper foils separated and protected by a 0.001-inch-thick layer of Mylar. The foils were connected to a coaxial cable and charged with a 150v bias voltage. When a projectile perforated the foils, the foil edges made contact and short the circuit

producing a "start" or "stop" pulse for the counter. The foil switches have proven again to be rugged, reliable, and accurate. All projectile speeds for the second series of experiments were determined from the foil switches.

2.2.2 Specimen Configuration (Titanium Projectiles and Titanium Targets).

The second set of one-third-scale experiments was conducted with a 14.5-mm powder launcher. The objective of the experiments was to determine the ballistic limit speed of 6Al-4V alloy titanium, high fineness ratio projectiles, centrally impacting 6Al-4V alloy titanium flat plates and the failure modes of the projectiles and the target. A full-scale titanium target plate is considered to be 0.75 inch thick, i.e., the thickness of a containment ring.

The titanium projectiles for the second series were 0.58 inch in diameter and were shaped as right-circular cylinders. Three projectile lengths were chosen corresponding to projectile fineness ratios of 10, 15, and 20. Projectile mass was 112, 168, and 226 grams, respectively. The projectiles were machined from 0.750-inch-diameter titanium bar stock. The materials specification was MIL-T-9047G, CONDITION A, AM 2 (6Al-4V titanium). Chemical analysis of the titanium stock yielded the following percentages of trace and alloying elements (the balance being titanium):

N: 0.0115	Fe: 0.1650
C: 0.0135	O2: 0.1750
H: 0.0032	Al: 6.2400
Y: 0.0010	V: 4.1100

Mechanical properties of the titanium bar stock were reported in reference 3:

Tensile Strength (ksi) (longitudinal):	152.3
Yield Strength (ksi) (0.2% offset):	141.9
Percent Elongation:	16.5
Percent Reduction in Area:	44.3

The target plates were composed of 6Al-4V alloy titanium. Some commercial aircraft jet engine containment rings are composed of titanium. The dimensions of the target plates were 6.0 by 6.0 by 0.25 inch. The materials specification was MIL-T-9046J, AM 2, AB-1, 6Al-4V titanium (AMS 4911H, 6Al-4V titanium). Chemical analysis of the titanium plate yielded the following percentages of trace and alloying elements (the balance being titanium):

N: 0.0090	Fe: 0.1650
C: 0.0150	O2: 0.1800
H: 0.0045	Al: 6.2200
Y: <0.0010	V: 4.0450

Mechanical properties of the titanium plate were reported in reference 3:

Tensile Strength (ksi)	
longitudinal:	138.0
transverse:	159.0
Yield Strength (ksi) (0.2% offset)	
longitudinal:	141.9
transverse:	147.0
Percent Elongation:	13.5
Percent Reduction in Area:	23.5

3. TEST RESULTS.

3.1 DATA FROM EXPERIMENTS WITH TITANIUM PROJECTILES AND ALUMINUM PLATE TARGETS.

Recorded below are the details of the 38 experiments performed against the 2024-T3 aluminum plate targets. For each experiment, the projectile impacted the target plate with the projectile's velocity vector perpendicular to the flat target plate, i.e., a normal impact.

Table 1 displays the details of seven ballistic experiments in which the titanium FSPs were launched against the 0.150-inch-thick aluminum plate targets. The mass of a typical FSP is 7.93 grams. In many cases, when a projectile perforated an aluminum plate target, not only was the projectile recovered, but also the aluminum "cap" (or "plug") created from the target plate during the process of plate perforation. Over the range of impact speeds for the experiments, the recovered FSP projectiles were examined and little or no permanent deformation was observed. The projectiles could have been reused. In three of the experiments, the speed of the projectile was estimated after perforating a target (Vres) using the radiographic technique described above.

TABLE 1. THE 0.50″ 6Al-4V TITANIUM FRAGMENT SIMULANT PROJECTILES AND 0.150″ 2024-T3 ALUMINUM PLATE TARGETS

Experiment No.	Vimpact (fps)	Perforation	Remarks
FAA-06	900 (Vres = 619)	Yes*	Projectile not deformed; target plug failure
FAA-07	694	No	Projectile lodged in target
FAA-13	868 (Vres = 504)	Yes*	Aluminum cap recovered
FAA-14	677 (Vres = 443)	Yes*	
FAA-33	469	No	
FAA-34	496	No	
FAA-41	583	No	Deep indentation and cracking

* Radiograph of projectile taken after projectile perforated target plate.

Table 2 displays the details of ten ballistic experiments in which the titanium RCC1s were launched against the 0.150-inch-thick aluminum plate targets. The fineness ratio of the RCC1 was 1.0. The mass of a typical RCC1 was 8.18 grams. The length of the RCC1 was equal to the length of the FSP. No apparent deformation of recovered RCC1 projectiles was observed. Target perforations were characterized as plug (shear) failures. In two of the experiments, the speed of the projectile was estimated after perforation of the aluminum target plate using the radiographic techniques discussed above.

TABLE 2. THE 0.50″ 6Al-4V TITANIUM RIGHT CIRCULAR CYLINDER PROJECTILE (FINENESS RATIO 1.0) AND 0.150″ 2024-T3 ALUMINUM PLATE TARGETS

Experiment No.	Vimpact (fps)	Perforation	Remarks
FAA-15	999 (Vres = 833)	Yes*	Target plug failure
FAA-16	650 (Vres = 295)	Yes*	
FAA-19	451	No	Projectile gas launched
FAA-28	471	No	
FAA-29	546	No	
FAA-30	588	No	
FAA-31	516	No	
FAA-32	696 (?)	Yes	Speed estimated by powder load
FAA-37	653	---	Projectile launch failure
FAA-40	668	Yes	Clean target plug failure

Table 3 displays the details of eight ballistic experiments in which the titanium FSPs were launched against the 0.100-inch-thick aluminum plate targets. Here, the target failure mode shown to be a tearing (petal) type when a target plate was deeply indented or perforated. In one experiment, the speed of the projectile after perforation of the aluminum target plate was estimated.

TABLE 3. THE 0.50″ 6Al-4V TITANIUM FRAGMENT SIMULANT PROJECTILES AND 0.100″ 2024-T3 ALUMINUM PLATE TARGETS

Experiment No.	Vimpact (fps)	Perforation	Remarks
FAA-08	545	Yes*	Target petal failure
FAA-09	589	No	Projectile may have pitched ?
FAA-10	543 (Vres = 481)	Yes*	
FAA-11	623	Yes	Target petal has projectile nose stamp
FAA-12	657	Yes	
FAA-17	416	No	Projectile gas launched
FAA-18	465	No	Symmetric indentation in target
FAA-35	522	No	Deep impression in target with tearing

Table 4 displays the details of seven ballistic experiments in which the titanium FSPs were launched against the 0.050-inch-thick aluminum plate targets. Here, the target failure mode continues to be tearing (petaling).

TABLE 4. THE 0.50″ 6Al-4V TITANIUM FRAGMENT SIMULANT PROJECTILES AND 0.050″ 2024-T3 ALUMINUM PLATE TARGETS

Experiment No.	Vimpact (fps)	Perforation	Remarks
FAA-20	271	No	Projectile nose stamped in target plate
FAA-21	351	No	Target petal attached
FAA-22	367	No	
FAA-23	424	Yes	
FAA-36	466	Yes	
FAA-38	423	No	Projectile found ahead of plate
FAA-39	403	No	Projectile found ahead of plate

Table 5 displays the details of six ballistic experiments in which the titanium RCC0.2 projectiles were launched against the 0.050-inch-thick aluminum plate targets. The fineness ratio of the RCC0.2 was 0.2. The mass of a typical RCC0.2 was 1.42 grams. Target perforations were characterized as plug (shear) failures.

TABLE 5. THE 0.50″ 6Al-4V TITANIUM RIGHT CIRCULAR CYLINDER PROJECTILE (FINENESS RATIO 0.2) AND 0.050″ 2024-T3 ALUMINUM PLATE TARGETS

Experiment No.	Vimpact (fps)	Perforation	Remarks
FAA-42	736	No	Deep indentation in target
FAA-43	591	Yes (?)	Projectile highly yawed at target
FAA-44	593	Yes (?)	Projectile highly yawed at target
FAA-45	1223	Yes	Target plug failure–new sabot for projectile
FAA-46	886	No	Deep indentation in target
FAA-47	880	Yes	Plug recovered; late time tearing

For the three FSP sets of experiments, projectile limit speed decreased in an almost linear manner with aluminum plate thickness. A simple, one-dimensional model for thin-plate shear plug failure by nondeforming projectiles [1] indicates such a linear relationship. At a plate thickness of 0.150 inch, the plate failure mode was by shearing. Figures 5 and 6 display the front and rear views of the target plates used in experiments FAA-14 and FAA-41. The nondeformed, recovered titanium projectiles are displayed along with the aluminum cap (plug) that was sheared from the target plate during impact. The target plate failure was a typical shear failure. In the nonperforated plate, (experiment FAA-41) observe the indentation caused by the chiseled nose of the FSP. For the two thinner target plates, the failure mode was by tearing, i.e., petal failure. Figure 7 displays typical aluminum plates recovered after impact and perforation with petal failures (experiments FAA-23 and FAA-39 with 0.050-inch-thick aluminum plate).

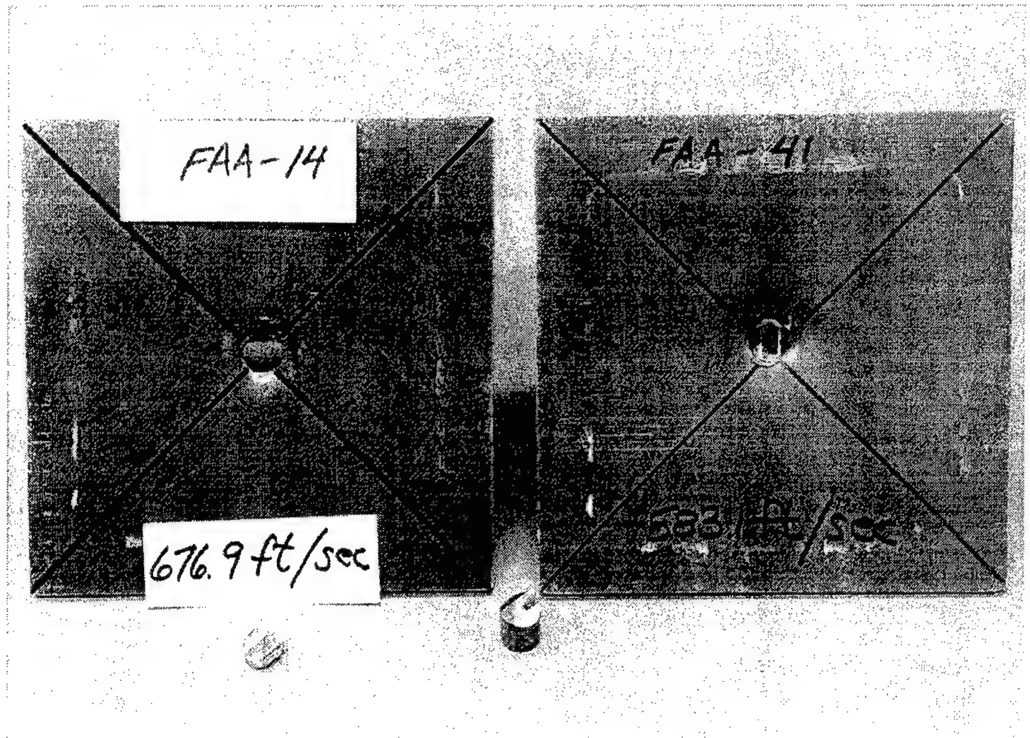

FIGURE 5. TYPICAL (0.150-inch-THICK) ALUMINUM PLATES—FRONT FACE

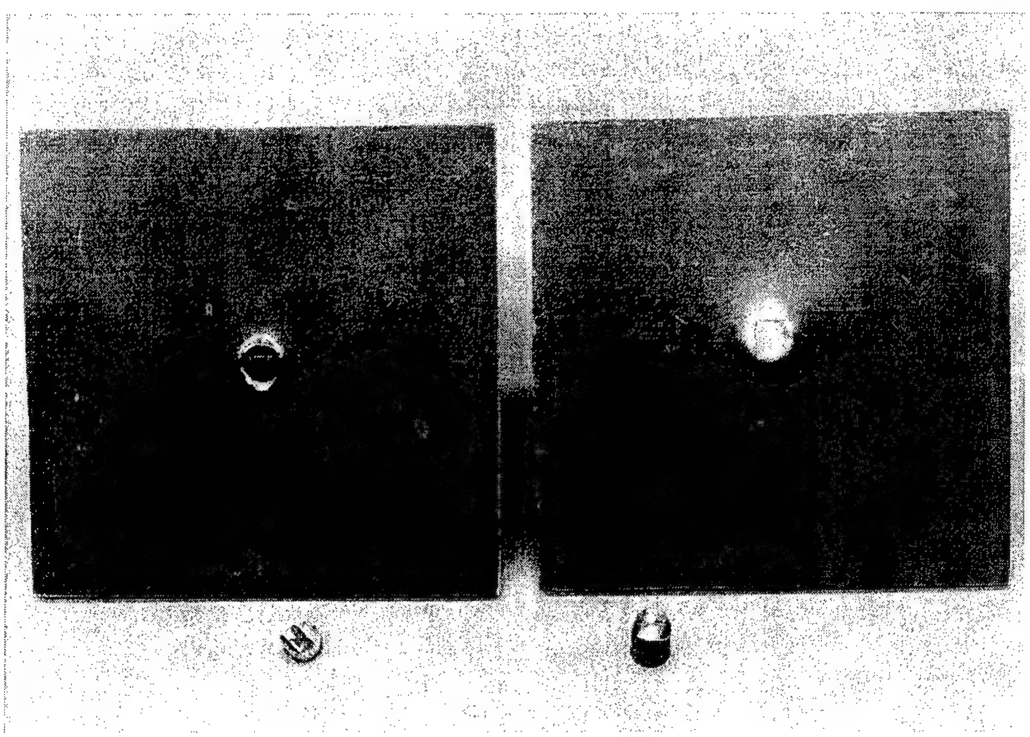

FIGURE 6. TYPICAL (0.150-inch-THICK) ALUMINUM PLATES —REAR FACE
(FAA-14 plug failure on left)

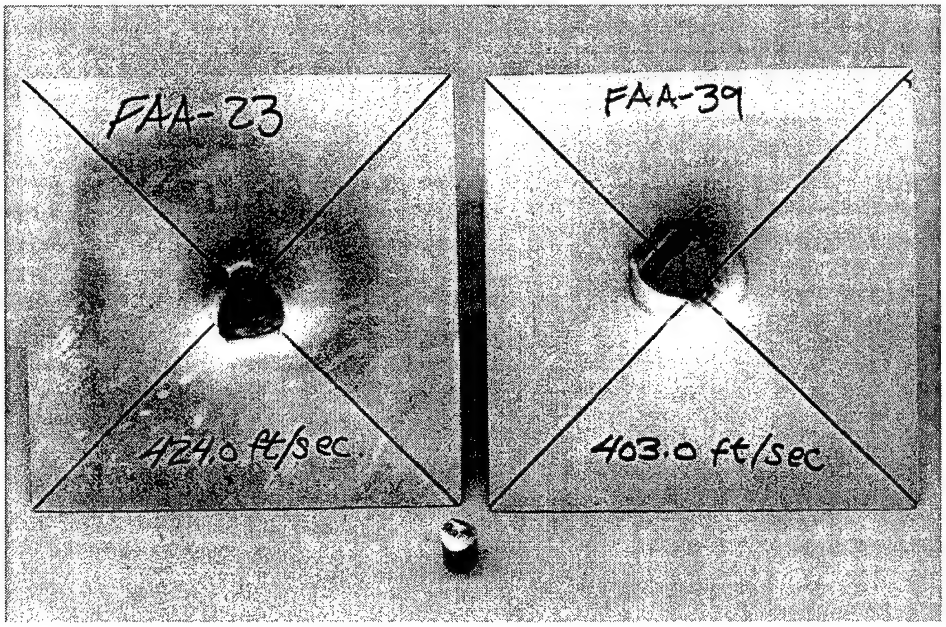

FIGURE 7. TYPICAL ALUMINUM PLATES WITH PETAL FAILURES—FRONT FACE

According to Irwin (5), there is a critical plate thickness at which the fracture mode of a propagating crack changes from a ductile to a brittle mode. Ductile fracture occurs when plate thickness is below the critical thickness; brittle fracture occurs when plate thickness is above the critical thickness. For 2024-T3 alloy aluminum, it was estimated that the critical plate thickness is between 0.135 and 0.325 inch depending on the values selected for tensile yield stress and critical stress-intensity factor. A change was observed in aluminum target plate failure mode due to projectile impact from tearing (petaling) to shearing (plugging) as plate thickness was increased from 0.10 and 0.15 inch.

Table 6 below summarizes the estimates of projectile limit speed for each combination of titanium projectile and aluminum target plate discussed above. For the experiments conducted in this series, no significant permanent deformation of the recovered projectiles was observed. The recovered projectiles could have been used again.

TABLE 6. SUMMARY OF PROJECTILE BALLISTIC LIMIT SPEEDS AND TARGET FAILURE MODES—ALUMINUM TARGET

Projectile (Titanium)	Target	Vbl (fps)	Failure Mode
Fragment Simulant Projectile (FSP)	0.150″ Plate	630 ±47	Plug (shear) Failure
	0.100″ Plate	533 ±11	Petal (tear) Failure
	0.050″ Plate	414 ±11	Petal (tear) Failure
Right Circular Cylinder Projectile (RCC1)	0.150″ Plate	619 ±31	Plug (shear) Failure
Right Circular Cylinder Projectile (RCC0.2)	0.050″ Plate	883 ±3	Plug (shear) Failure

The RCC1 titanium projectile had a mass about 3.0% larger than the FSP projectile. The diameter and length of the RCC1 projectile was the same as the FSP projectile. The only difference was that the RCC1 projectile has a blunter nose. On the basis of the limit speeds of the two projectiles against the same aluminum plate target (thickness of 0.150 inch), it can be concluded that the small increase in projectile nose bluntness did not affect projectile limit speed. The simple shear plug model indicates that a 3.0% increase in projectile mass lowers projectile limit speed by 1.5% against the same target. The target plate failure mode was the same for the RCC1 and FSP projectiles—shear plug failure.

The RCC0.2 titanium projectile had a mass about 18% of that of the FSP projectile. The diameter of the RCC0.2 projectile was the same as that of the FSP projectile. To insure that the sabot produced an insignificant impact effect on the aluminum targets, the sabots were machined from polyurethane foam (specific gravity of 0.2 gm/cc). The sabot geometry was a hollow right circular cylinder with fineness ratio of one and was such that a projectile front face was flush with a sabot face.

Using the simple plug model, it was expected that a change in fineness ratio from 1.0 to 0.2 would increase the limit speed by a factor of 2.35. Had the failure mode of the titanium FSP against the 0.050-inch-aluminum target plate been a shear failure, it would be expected that the RCC0.2 projectile limit speed would have been about 973 fps (414 fps $\times$ 2.35). However, the 0.050-inch-aluminum plate failure mode was a petal failure. This implies that the 973-fps estimate is only an upper bound. For a selected projectile and target, which undergoes transition from plug to petal failure as target plate thickness is decreased, it appears that a smaller percentage of the projectile's kinetic energy at impact is transferred to the plate when the plate undergoes a shear (plug) mode failure than when it undergoes a petal (tear) mode failure [1]. This implies that projectile limit speed could be lower for a shear failure than for a petal failure, all else held constant (i.e., if the plate had a choice of failure mode). Again, no deformation was observed for the recovered RCC0.2 projectiles.

3.2 DATA FROM TITANIUM PROJECTILES AND TITANIUM PLATE TARGET EXPERIMENTS.

Recorded below are the details of the ten experiments performed against the 6Al-4V alloy titanium plate targets. For each experiment, the projectile impacted the target plate with the projectile's velocity vector perpendicular to the flat target plate, i.e., a normal impact.

Table 7 displays the details of ten ballistic experiments in which the titanium projectiles were launched against the 0.250-inch-thick titanium plate targets. For the three experiments conducted with projectiles of fineness ratio of 20, the target was perforated during each experiment. This was also the case for the experiments with projectiles of fineness ratio of 10. For the experiments with projectiles of fineness ratio of 15, the limit speed could be estimated (see table 8). As described in paragraph 2.2.1, foil switches were used to determine the velocity of a projectile before impact with a target. In this test, the projectiles are relatively massive (compared to the foil switch triggers). There was no concern about projectile damage or disruption when encountering a foil switch.

TABLE 7. THE 0.58″ 6Al-4V TITANIUM PROJECTILES AND 6Al-4V TITANIUM PLATE TARGETS

Projectile L/D	Experiment No.	Vimpact (fps)	Perforation	Remarks
20	FAA-51	1427	Yes	RP (0.560 inch) *
	FAA-55	817	Yes	RP (0.410 inch)
	FAA-56	571	Yes	RP (0.060 inch)
15	FAA-57	559	Yes	RP (0.045 inch)***
	FAA-58	377	No	Slight target plate bulge
	FAA-59	454	No	Substantial target bulge
10	FAA-52	1262	Yes	RP (0.350 inch)
	FAA-53	1029?	Yes	RP (0.150 inch)**
	FAA-54	795	Yes	No result at witness block
	FAA-60	608	Yes	RP (0.000 inch)

* RP is the residual penetration into a 6- by 6- by 4-inch-thick 6061-T6 alloy aluminum witness block.

** The foil switch triggered late. One thousand twenty-nine fps is a speed estimate from the mass/load launcher data.

*** Two crescent shaped nicks in the witness block with maximum depth of penetration of 0.045 inch.

Table 8 below summarizes the estimates of projectile limit speed and lower bound for projectile limit speed for the titanium projectiles and the titanium target plate discussed above. For the experiments conducted in this series, projectile damage due to target impact was slight at best. One could observe visually a very slight "mushrooming" of the blunt projectile nose when examining the projectiles after the experiments. It would be a good approximation to assume that the projectiles penetrated or perforated the targets as rigid bodies.

TABLE 8. SUMMARY OF PROJECTILE BALLISTIC LIMIT SPEEDS AND TARGET FAILURE MODES

Projectile Fineness Ratio	Vbl (fps)	Failure Mode
20	< 571	Plug (shear) Failure
15	507 $\pm$52	Plug (shear) Failure
10	< 608	Plug (shear) Failure

The simple, phenomenological model for thin plate shear plug failure by nondeforming projectiles [1] indicates that if the limit speed for the projectile with fineness ratio of 15 is about 480 fps, then the corresponding limit speeds of the projectiles with fineness ratios of 10 and 20 would be about 590 fps and 420 fps, respectively. These estimates are consistent with the ballistic data above.

For each projectile, the titanium plate failure mode is by plugging (shear failure). Many of the titanium plugs were recovered after the experiments. The plug diameter was just slightly larger than projectile diameter. Recovered titanium projectiles were almost without any observable damage. The target plate failure was a typical shear failure.

4. SUMMARY.

Two sets of fundamental experiments in penetration mechanics were conducted in the Lawrence Livermore National Laboratory Terminal Ballistics Laboratory of the Physics Directorate. The first set of full-scale experiments conducted with a 14.5-mm air propelled launcher. The object of the experiments was to determine the ballistic limit speed of 6Al-4V alloy titanium, low-fineness ratio projectiles centrally impacting 2024-T3 alloy aluminum flat plates and the failure modes of the projectiles and the target.

During the course of the experiments, no significant permanent deformation was observed for any of the recovered projectiles. At a plate thickness of 0.150 inch, the plate failure mode was shearing, i.e., a plug failure. For the two thinner target plates, thickness of 0.10 and 0.050 inch, the plate failure mode was tearing, i.e., petal failure. The critical plate thickness for the failure mode transition from tearing to shearing due to projectile impact was consistent with the critical plate thickness associated with the fracture mode transition of a propagating crack, i.e., ductile to brittle fracture. For 2024-T3 alloy aluminum, it was estimated that the critical plate thickness for the transition in crack fracture mode was between 0.135 and 0.325 inch depending on the values selected for tensile yield stress and critical stress-intensity factor. A change in aluminum target plate impact failure mode from petaling to plugging was observed as plate thickness increased from 0.10 and 0.15 inch.

The second set of one-third scale experiments was conducted with a 14.5-mm powder launcher. The object of these experiments was to determine the ballistic limit speed of 6Al-4V alloy titanium, high-fineness ratio projectiles centrally impacting 6Al-4V alloy titanium flat plates and the failure modes of the projectiles and the target.

For these experiments, it was observed that projectile damage due to target impact was slight at best. One could visually observe a very slight mushrooming of the blunt projectile nose when examining the projectiles after the experiments. It would be a good approximation to assume that the projectiles penetrated and perforated the targets as rigid bodies.

For each of the three projectiles evaluated, the titanium target plates failed by plugging (shear failure). Titanium plugs, just slightly larger than the projectile diameter, were sheared out of the target plate ahead of the penetrating projectile. In many cases, projectiles were recovered almost without any observable damage.

The data from this testing will be used to update the DYNA-3D model codes and submitted to the FAA under this contract.

5. REFERENCES.

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2. MIL-T-9047G, "Titanium and Titanium Alloy Bars (Rolled or Forged) and Reforging Stock, Aircraft Quality," Naval Air Systems Command, April 1998, available from Defense Automation and Procurement Service.

3. ASTM-B-209, "Standard Specification for Aluminum and Aluminum Alloy sheet and Plate," 1996 Annual Book of ASTM Standards, Vol. 2. 02, American Society for Testing and Materials, Philadelphia, PA.

4. AMS 4037, "Aluminum Alloy Sheet and Plate 4.4 Cu-1.5 Mg-0.6 Mn (2024-T3 Flat Sheet, -T351 Plate) Solution Heat Treated," Society of Automotive Engineers, Non-Ferrous Alloys committee, January 1993.

5. "Fracture Mode Transition for a Crack Traversing a Plate," G.R. Irwin, *Journal of Basic Engineering,* Transactions of the ASME, June 1960.

6. DEFINITION OF TERMS.

Ballistic limit/ballistic limit speed—The velocity at which a projectile causes sufficient damage to a target that the projectile or projectile debris can be considered to have accessed the space behind the target.

Ballistic threshold—Same as ballistic limit/speed.

Cap (plug) failure—A failure mode characterized by a sheared region extending through the thickness of the target and peripheral to the outer boundary of the projectile.

Chronograph—Any device used to measure time. Here it is used to measure the time interval between flash x-rays. Combining time and distance information allows one to determine velocity.

Conventional flash radiography—This refers to the use of pulsed x-rays sources to obtain snapshots of the position, shape, and orientation of an object.

DYNA-3D—DYNA-3D is a popular finite element code that has been extensively used for nonlinear, large deformation mechanics modeling.

Fineness ratio—Here it is used to specify the ratio of length to diameter for the projectiles.

Foil switch trigger—a foil switch consists of two thin layers of a conducting material separated by a layer of insulating material. A charge is applied to the conductors. When impacted, the foil breaks down allowing current to flow and be detected. This can be used to provide time of arrival data.

Fragment simulant projectile—This refers to a U.S. Department of Defense specified shape that is used as a fragment mock in studies of damage assessment.

Full-Scale—"Full-scale" refers to the utilization in tests of dimensions approximately the same as those encountered in the actual physical configurations of interest.

Gas breech—A gas breech is a volume filled with high-pressure gas that is used to accelerate an object.

Mitigation containment technology—This phrase is redundant. The appropriate reference should be to containment technology. Containment can always be considered as a form of mitigation.

Penetration mechanics—The science or methodology of understanding the dynamics of the interaction of a projectile with a target given that the projectile has sufficient velocity to generate material deformations in either the projectile or the target or both.

Petal failure—A failure mode characterized by significant bending followed by failure initiated in a localized region with cracks or shear lines radiating out from the position of the initial failure. The multiple cracks or tears bend backwards from the momentum of the projectile, causing a shape reminiscent of a petal.

Phenomenological model—A model that is based on general physical tendencies or observed trends in data, rather a precise representation of any individual event.

Projectile—this refers to the body that has been accelerated by some means and directed towards the target.

Projectile limit speed—Same as ballistic limit speed.

Projectile residual penetration—This refers to the capacity of a projectile to penetrate material after it has already penetrated the target of interest.

Projectile trap—The position in the gun assembly where the projectile/sabot assembly is seated prior to acceleration.

Radiography—This refers to the use of pulsed x-rays sources to obtain snapshots of the position, shape, and orientation of an object.

Right circular cylinder/projectile—A cylinder with flat faces perpendicular to the axis of the cylinder.

RCC—An acronym representing the term "right circular cylinder" used to label projectiles of various dimensions.

Sabot—This is an object that couples the projectile, which may be of irregular shape, to the gun barrel, which is cylindrical. It is designed to separate from the projectile prior to impact.

Target—The structure that is used to assess the damage caused by interaction with the projectile.

Ullage—Ullage refers to the unfilled volume in a partially filled container.

Ullage fillers—An ullage filler is some inert object or material other than the contained material that is used to take up a fraction of the ullage.

V impact—The initial velocity of the projectile at the time of impact.

V res—The residual velocity the projectile might have after penetrating the target.